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Underwater Sound Transducer Calibration Facility for the 10- to 4000-Hz Frequency Range at Hydrostatic Pressure to 10,000 psig

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ABSTRACT

A new controlled-environment facility operating on the principle of active-impedance termination in a rigid-walled tube now provides the means of calibrating a wide variety of underwater sound transducers in the increasingly important frequency range 10 to 4000 Hz at static pressure to 10,000 psig and temperature from 3 to 45°C. This report describes the theory, limitations, and mechanical features of the facility and presents examples of both primary and secondary calibrations of transducers in the tube and in a free field.

PROBLEM STATUS

This is an interim report on the problem.

PROBLEM AUTHORIZATION

NRL Problem S02-30

Project RF 05-111-401-4471

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CONTENTS

ILLUSTRATIONS

UNDERWATER SOUND TRANSDUCER CALIBRATION FACILITY
FOR THE 10- TO 4000-Hz FREQUENCY RANGE
AT HYDROSTATIC PRESSURE TO 10,000 psig

INTRODUCTION

For many present-day applications of underwater sound transducers, the user requires information about the effect on performance of variation in hydrostatic pressure and temperature. Considerable effort has been devoted--both at this laboratory and elsewhere [1-6]--to the development of techniques and equipment for providing this kind of information. This report deals with the acoustic theory and the mechanical details of a second-generation calibration facility based on concepts [7,8,9] that have provided a breakthrough in controlled-environment calibration techniques. The electronics system and the acoustical instrumentation of the new facility are reported separately [10,11].

Both the new System "J" and the older USRD "Tube Facility" can provide primary and secondary calibrations on a wide variety of transducers in ranges of frequency, pressure, and temperature heretofore unobtainable. System J provides primary reciprocity calibrations in the frequency range 500 to 4000 Hz. Secondary calibrations can be made from 10 to 4000 Hz, which represents a considerable extension of the 100- to 1500-Hz range available in the Tube Facility. The low-frequency limit is imposed by inability to generate a useable signal level below 10 Hz with the present amplifier-transducer combination.

The upper limit of static pressure also has been increased from 8500 psig available in the Tube to 10,000 psig in System J. Finally, the new facility provides control of water temperature from 3 to 45°C. Lower temperatures can be attained by adding antifreeze solution to the water. Temperature control in the older facility is limited to heating only.

THEORY

Both the primary and the secondary calibration procedures used in System J at frequencies above 500 Hz are based on the principle of active-impedance termination. The primary calibration procedure is a reciprocity method involving the plane-wave reciprocity parameter and is somewhat analogous to that in free-field reciprocity. A detailed discussion of these techniques can be found in references [7] and [8].

Standing-wave effects are less significant below 500 Hz, and the use of active-impedance termination in the secondary calibration process is not normally important at these frequencies unless the transducer has a sharp, lightly damped resonance in this range.

For active-impedance termination, a sound source is placed at each end of a sound channel--in this case, a water-filled stainless-steel tube. Both sources are driven electrically at the same frequency; the relative amplitude and phase of the two are adjustable, so that one of the transducers acts as a source and the other as a load impedance. With suitable adjustment, the characteristic impedance of the longitudinal mode of wave propagation in the channel can be matched; plane, progressive waves are created in the medium, and the conditions for free-field calibration of a transducer are simulated in the sound channel.

Two important factors affecting a calibration under these simulated free-field conditions are (1) the effect of wall proximity on the transducer being calibrated, and (2) the frequency independence of the resistive part of the radiation load that the transducer sees in the channel as a projector. The wall effect is predominant only on resonant, high-Q transducers, and is a function both of the ratio of the area of the transducer to the cross-section of the channel and the frequency at which the resonance occurs. The lower the frequency at resonance and the smaller the Q, the less noticeable is the effect.

Insofar as the receiving sensitivity of the transducer is concerned, the effect of wall proximity is to decrease the normal free-field radiation mass loading. Thus, a resonance occurs at a higher frequency in the channel than it does in a free field. If free-field results are available, the data on resonant transducers can be corrected empirically. The corrections so arrived at are virtually independent of pressure and temperature and thus can be used to convert the channel results to free-field equivalence at any combination of pressure and temperature conditions available in the facility. An example of the Tube Facility calibration of a resonant transducer is shown in reference [9], Fig. 4.

The transmitting response in the channel is affected both by the mass loading change, if the transducer is resonant, and by the frequency independence of the radiation resistance loading. Nevertheless, an equivalent free-field transmitting response can be obtained from the transmitting response measured in the channel. For low-Q or nonresonant reciprocal transducers, the free-field transmitting response will be the product of the channel transmitting response and the ratio of the channel plane-wave reciprocity parameter J_p to the free-field reciprocity parameter J_s. The general expressions are:

$$J_p = (2A/\rho c),$$

$$J_s = (2d\lambda/\rho c);$$

then,

$$J_p/J_s = A/d\lambda ,$$

where A is the cross-sectional area of the channel, ρ is the density of the medium in each case, c is the speed of sound in the medium, λ is the wavelength at the frequency of interest, and d is the distance in the free field between the hydrophone being calibrated and the auxiliary transducers required in the reciprocity measurement.

For a resonant transducer that is reciprocal in the free field, a free-field transmitting response can be obtained from a corrected channel receiving sensitivity by applying the free-field reciprocity parameter. Changes that occur in sound speed with pressure and temperature, as well as the difference between sound speed in the tube and that under free-field conditions must be accounted for; further, it must be assumed that the transducer remains reciprocal as these parameters vary. High-Q resonant transducers are not reciprocal under the active-termination loading created in the channel. (See reference [8], page 45.)

PHYSICAL ARRANGEMENT

Although both primary and secondary calibrations can be made, most measurements are made by the secondary, or comparison technique because of its simplicity. Figure 1 shows the physical arrangement used in making

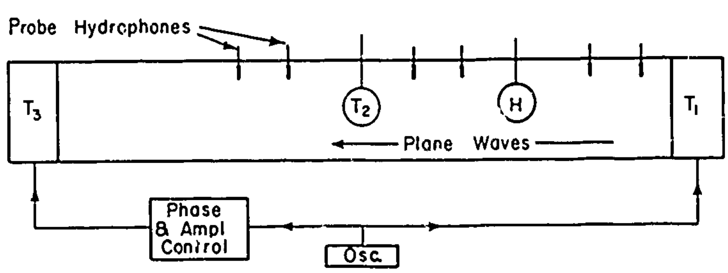

Fig. 1. Single-termination arrangement for secondary calibration in a plane, progressive wave; T_1 is the source; T_3 is the terminal transducer; T_2 and H are unknown or standard transducers.

secondary measurements at frequencies above 500 Hz. The transducers at each end serve either as a sound source or an active-impedance termination, as may be desired. At a given frequency, the conditions leading to a plane-wave termination are monitored by measuring the relative phase and amplitude of the acoustic pressures impinging on two probe hydrophones at predetermined spacing. As many as 6 probes are available; they can be spaced at various intervals along the length of the channel to allow good detection sensitivity throughout the operating frequency range. The transducer T_2 to be calibrated is rigged between these probes and the terminating transducer T_3. After plane, progressive waves have been established, the detection probes serve as reference standards to measure the sound pressure to which the unknown transducer is subjected.

Absolute acoustic calibration of the probes as a function of static pressure can be made by the primary method in the System itself, or in a specially designed coupler similar to that described in reference [4]. Calibration in the System can be made also as a function of temperature; there is the disadvantage, however, that, to obtain absolute calibration with respect to either pressure or temperature, knowledge of the relative sensitivities of the probes is required as a starting point.

Any change in these relative sensitivities with pressure can be measured directly in the coupler, and can be detected in the System for both pressure and temperature changes by monitoring for uniformity of sound speed between pairs of probes when the System is properly terminated for the production of plane, progressive waves.

Because of the excellent design and careful construction of the probes, neither temperature- nor pressure-related variation in these relative sensitivities has been observed.

DIRECTIONAL EFFECT

Normally, the unknown transducer is rigged so that its axis of maximum sensitivity is directed toward the source and coincides with the axis of the channel. On some transducers, however, sensitivity measurements must be made off axis. For example, a line transducer whose diameter is small in comparison with that of the channel is measured in the end-fire direction.

SOUND SPEED

Sound speed in the chamber has been determined in two ways: At 0 psig pressure, the bottom transducer was used to drive the chamber when it was water filled and open to the air at the upper end. Plots were made of the standing-wave pressure field under these conditions as a function of distance along the chamber at discrete frequencies. Sound speed was determined from the operating frequency and the distance between the nodes and antinodes of the standing-wave plot. These plots also served to show the lack of interference of possible mechanical structural resonances with the sound field in the water medium of the chamber. A typical standing-wave plot for 4000 Hz is shown in Fig. 2.

After a preliminary value of sound speed had been found in this way, the channel was closed and this value of the speed was used as a starting point in establishing plane progressive waves. The terminal conditions were adjusted until the sound-pressure wave acting on each acoustic probe reached the desired relationship of constant amplitude and constant phase per unit distance between all six probes.

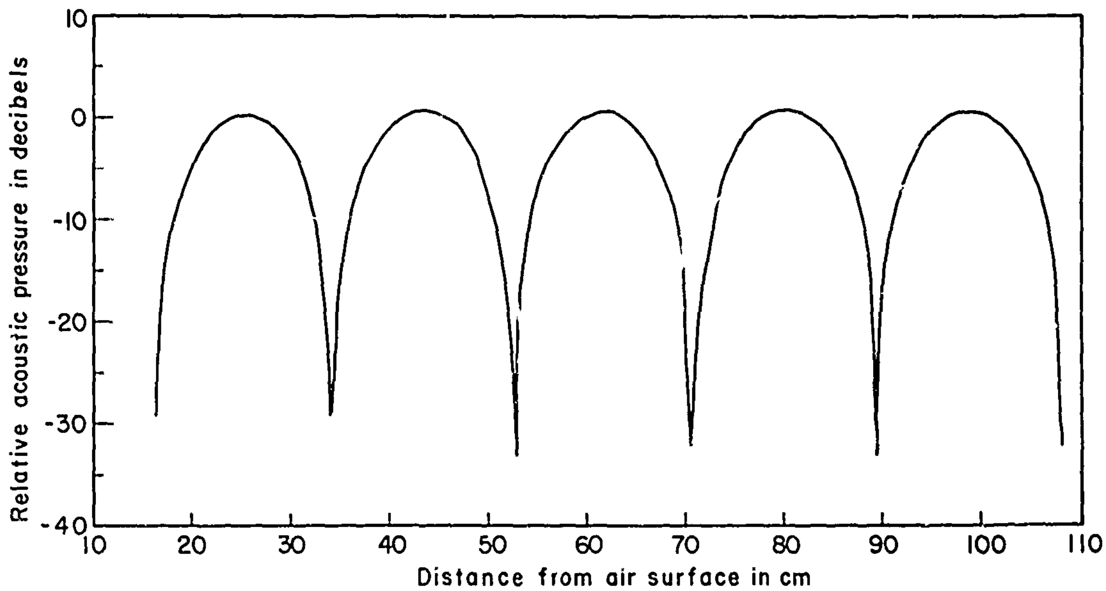

Fig. 2. Pressure standing wave at 4000 Hz.

The final value was the average speed determined from measurements of the probe spacing and the corresponding time delay. At pressures higher than atmospheric, it was necessary to rely on this latter method altogether, starting at 0 psig and gradually working up to maximum pressure.

The sound speed measured with the chamber filled with deaerated fresh water at 0 psig and 24°C was 1.460×10^5 cm/sec, which is roughly 98% of the free-field speed as measured by Wilson [12]. This is in good agreement with Korteweg's theory on sound speed in water-filled steel tubes, as discussed by Kuhl [13]. Higher speeds can be obtained with larger ratios of wall thickness to internal radius; however, the ratio of increase in speed to the increase in chamber mass diminishes rapidly. The 98% value represents a ratio of wall thickness to internal radius of approximately 0.85, which has been deemed suitable for static pressure requirements and gives an adequate sound speed. The speed at 10,000 psig increases to 1.575×10^5 cm/sec. Adding ethylene glycol to prevent freezing raises the sound speed above that of fresh water; for a 20% solution, the speed becomes 1.560×10^5 cm/sec at 24°C and 0 psig. Indications are that the speed of propagation of sound in sea water could be closely matched.

ACOUSTICAL DESIGN PARAMETERS

Of the several factors affecting the acoustical design of the system, the operating frequency range is of primary importance. The upper limit is established by the cutoff frequency of the lowest radial mode in the chamber. This, in turn, depends upon the sound speed in the medium and the internal diameter of the chamber. The frequency 4000 Hz was chosen as the upper limit to give the highest range possible consistent with keeping the inside diameter of the chamber large enough to accept the wide variety of transducers received for calibration. The lower limit for primary calibration was chosen as 500 Hz to provide for a sufficient overlap between the frequency range of the new facility and the present USRD 8500-psig Tube Facility, and at the same time to keep to a practical value the tube length for which termination would be detected at lower frequencies. These requirements, along with those of static pressure, weight, and economic considerations, led to the choice of a stainless-steel chamber 274.32 cm long with wall thickness 8.57 cm and the i.d. 20.32 cm. Stainless steel was selected as the material to minimize corrosion, particularly at the pressure-sealing surfaces.

The chamber was designed to provide minimum mechanical coupling between the electroacoustic driving sources and the walls by fitting a steel plug into each end as a closure. The driving transducers are mounted on these plugs, and O-rings between the plugs and the chamber walls seal the pressure. The chamber is vertically mounted; the end plugs are held in place while the system is under pressure by placing the chamber within a strongback frame. Excluding the end plugs and driving transducers, the working length of the chamber is 206 cm.

Because no bolts or threads are required, the strongback arrangement serves also as a means of obtaining quick access to the inside of the chamber (Fig. 3). The electrical leads to the bottom projector are brought out through high-pressure fittings built into the bottom plug. The rest of the acoustical instrumentation and the transducer being calibrated are attached to the top plug in a specially designed 3-section cylindrical cage. The electrical connections to the acoustical instrumentation and to the transducer are brought out through high-pressure fittings in the top plug. Thus, all of the acoustical instrumentation except the bottom transducer can be removed at one time by removing the top plug. Normally, the bottom transducer is not removed except for repairs, in which case the chamber is lifted off the bottom plug by an external hoist. The mechanical rigging and the acoustical instrumentation have been designed to keep obstructions within the chamber to a minimum.

Figure 3 is a picture of the top plug and its associated transducer and rigging, together with a hydrophone rigged for calibration. Two of the acoustical probes used for monitoring terminal conditions can be seen in the lower left side of the rigging cage. The other probes are farther down the cage and inside the chamber.

MECHANICAL DETAILS

The system is housed in the two-story USRD low-frequency building, which was designed particularly to meet the needs of System J and those of an older tank calibration system that operates at lower frequencies and pressures.

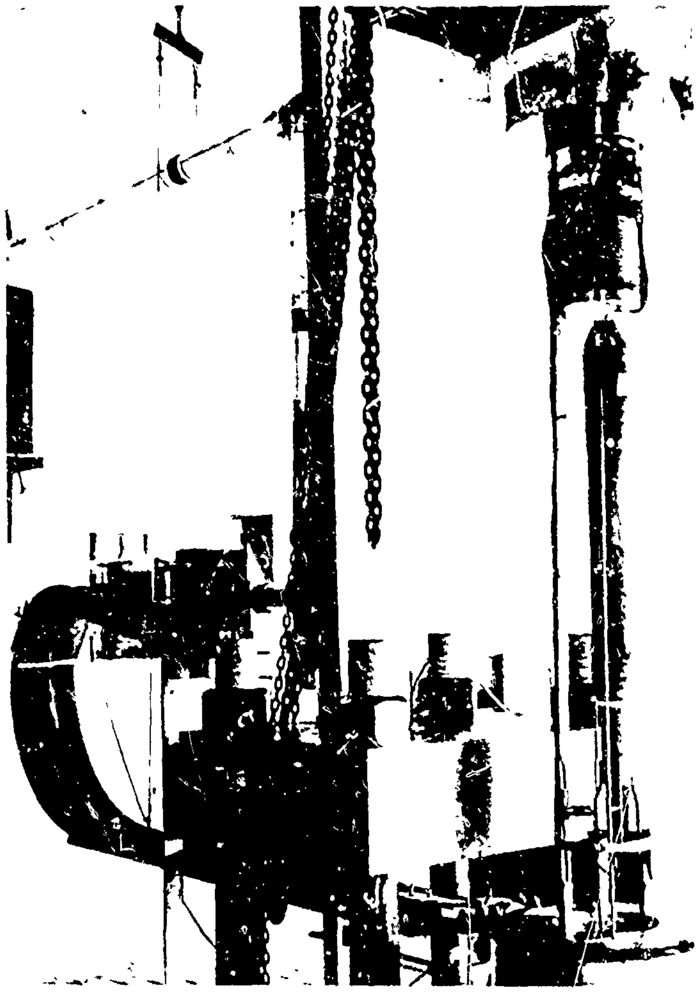

Fig. 3. Top plug and transducer (upper right), with hydrophone rigged for calibration.

The system chamber and its mechanical equipment are located on the ground floor. As a safety measure, they are mechanically shielded from the rest of the building by a floor-to-roof reinforced-concrete wall. Part of the second floor is used as a rigging room and part for a control and measurements room, which is isolated from the rigging room by the concrete wall.

To provide acoustical isolation from low-frequency ground noise, the chamber and its strongback frame have been mounted on a 6800-kg cement block. The concrete was poured into a pit 1.2 m on a side in the building floor. The sides of the pit were first lined with a 10-cm-thick layer of cork and then covered with a sheet of vinyl building plastic before the concrete base was poured. The top part of the base forms a pedestal that serves to hold the bottom bolster block of the strongback and provides a stand to hold the chamber when it is removed from the frame.

The strongback frame consists of two 25.4-cm-thick carbon steel bolster blocks 71.1 cm wide and 91.5 cm long, separated by four 10.8-cm-dia steel rods 3.9 m long threaded on each end to accept spacing nuts and clamping nuts on the bolster blocks.

The chamber is moved into and out of the strongback frame on a hydraulically controlled track arrangement that lifts and lowers the chamber and rolls it in and out. Clearance is allowed between the bolster and the end of the chamber to accommodate the lifting process. While the chamber is under pressure, this clearance is partly taken up by a removable metal plate slipped in between the top of the chamber and the top bolster block, and partly by the protrusion of the top end plug, for which clearance is allowed in the seal areas. Figure 4 is a ground-floor view of the vessel sitting in its strongback frame.

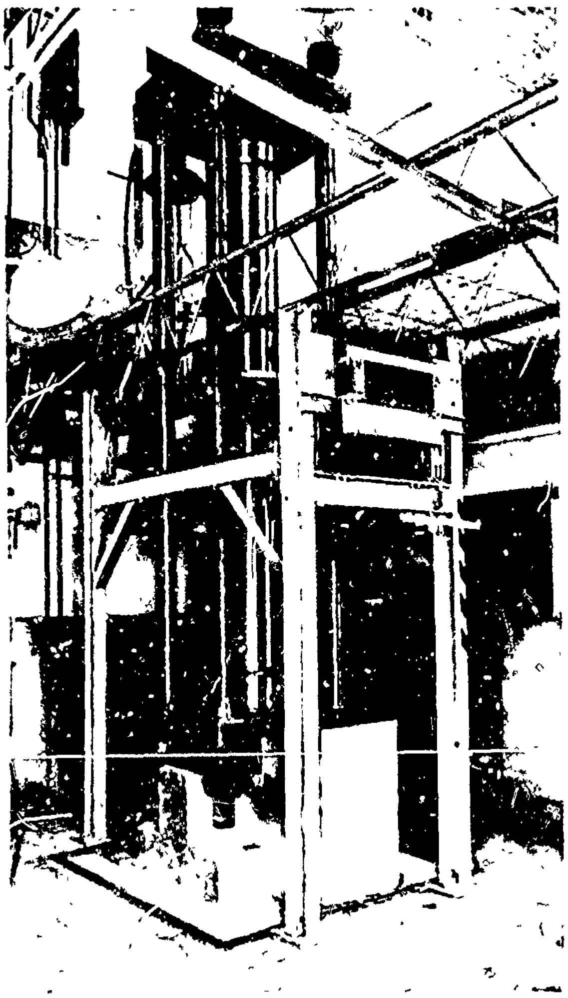

Fig. 4. General view of System J.

As it rests on its base, the top of the chamber protrudes into the second floor of the system room. This floor is constructed of removable metal grating, which provides easy access to the top of the chamber so that instrumentation can be rigged, and also allows the passage of equipment between floors. Heavy equipment is handled by a hoist supported from a ceiling-mounted track on center with the chamber, so that the hoist can be used also to remove the top end-plug or to lift the chamber itself when necessary.

The control and measurements room, as previously mentioned, is located behind the reinforced-concrete wall on the second floor of the building. An iron-shuttered window in this wall enables the operator to view the chamber and provides protection in the event of any mishap during pressurization. This window can be seen at the rear in Fig. 3.

To eliminate trapped air, which is detrimental to system performance, the chamber is connected top and bottom into a closed-circulation system. This allows the water to enter and be circulated through the chamber under vacuum. Connection to the external piping is made by flexible high-pressure hoses; thus, it is unnecessary to disconnect pipe when the chamber

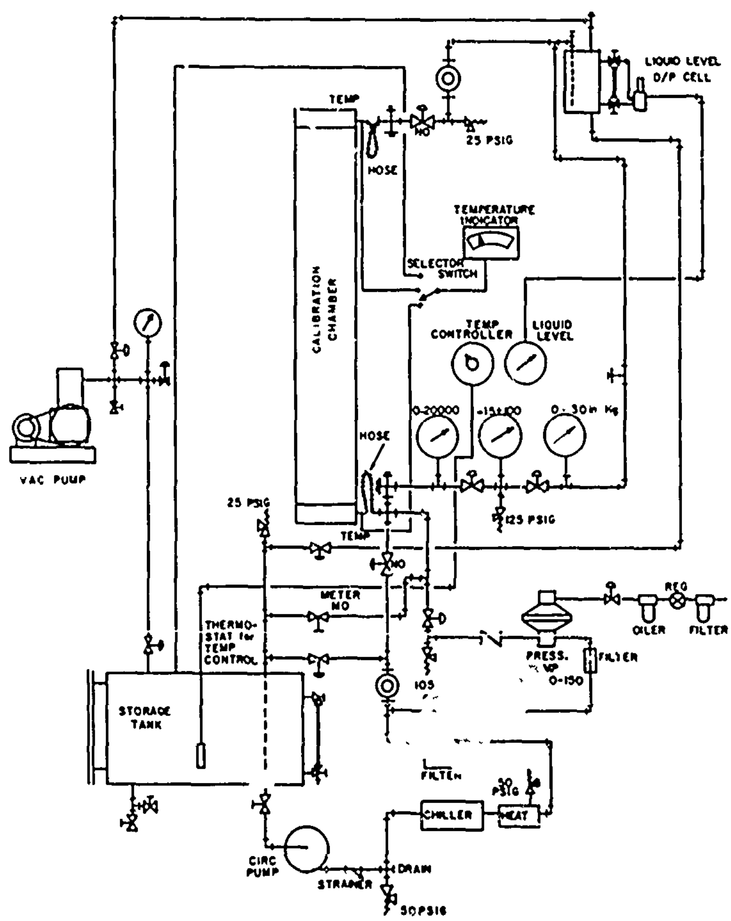

Fig. 5. Diagram of piping, pumps, valves, and meters.

is moved. These hoses are shown at the rear of the bolster blocks, Figs. 3 and 4. The use of 3 hoses gives adequate flexibility and water flow while withstanding the required 10,000-psig pressure. Figure 5 is a simplified diagram of external piping. All high-pressure piping is of stainless steel with lens-type couplings. All valves associated with the normal system operation are remotely operated, with air-operated actuators. All electric components and gages also are remotely operated.

All of the normal mechanical functions except that of moving the chamber are controlled from a specially designed console in the control and measurements room (Fig. 6). Laid out on the sloping face of this console is a simplified diagram of the piping arrangement with each control beside its location in the diagram. Indicator lights show the off or on condition of the control.

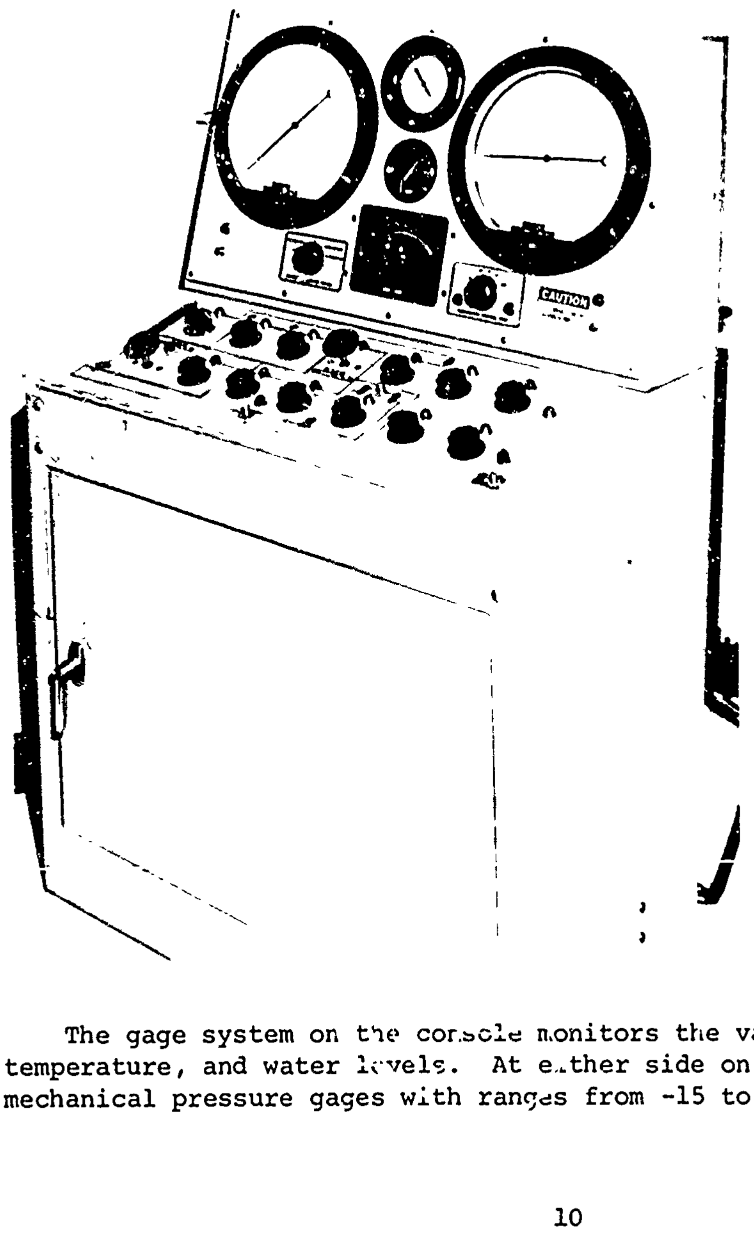

Fig. 6. Control console.

The gage system on the console monitors the vacuum, static pressure, temperature, and water levels. At either side on the upper panel are two mechanical pressure gages with ranges from -15 to +100 psig in 1-psi units and from 0 to 20,000 psig in 50-psi units. In addition, a smaller vacuum gage (top center) monitors the storage tank vacuum. The gage shown in the center of the upper panel monitors the water level in the small overflow tank while the chamber is being filled. The temperature is monitored at the top and bottom ends of the chamber, as well as inside the storage tank. These temperatures are indicated on the gage in the center at the bottom of the upper panel. At the sides of this gage are the temperature location selector switch and the temperature controller dial by which the desired water temperature is set and controlled.

Because water cannot be circulated during calibration, the system storage chamber, piping, and calibration chamber are jacketed in a 2.5-cm-thick coat of rigid foam plastic. Thermal drift in the chamber at 3°C is less than 1.0° per hour.

The chamber is pressurized by pumping extra water into it with an air-operated high-pressure water pump. To raise the pressure in the chamber to 10,000 psig requires 2740 cm^3 additional water, or about 10 min of time at maximum pumping speed. Static pressure is reduced by releasing water from the chamber by an air-operated variable-orifice valve; for very low depressurization rates, a hand-operated needle-valve and high-resistance pipe arrangement is used.

The circulation system allows the chamber to be filled and drained under vacuum and the water in the storage tank to be kept under vacuum when not in use.

The calculated natural frequency of the first radial resonance of the chamber walls with water loading is above 10,000 Hz. The first longitudinal resonance of the free steel chamber is approximately 900 Hz. None of the longitudinal resonances have any noticeable effect on the internal sound field.

OPERATIONAL CHARACTERISTICS

In the range 500 to 4000 Hz where termination is used, typical sound pressure levels of 70 dB re 1 μbar can be attained. The level below 500 Hz gradually decreases to 55 dB at 10 Hz. Effective wide-band noise level at the output of the system-probe channels is equivalent to an acoustic input noise pressure of about 35 dB in the operating frequency range.

The accuracy of a primary calibration depends upon the extent to which the desired termination is achieved, the accuracy of the current-measuring system, and the type of transducer being calibrated. Nominal accuracy for transducers that are nonresonant or for which $Q < 5$ at resonance is ±0.5 dB. For secondary calibrations, accuracy decreases somewhat because of the dependence upon the accuracy of the comparison standard. Normally, this standard is one of the system detection probes or the result of an average of several of these probes, depending upon whether or not measurements are being made under plane-wave conditions; in all cases, however, the accuracy is within ±1 dB. Calibrations on transducers resonant above 500 Hz can be obtained at all static pressures and temperatures to ±1-dB accuracy by applying an empirical correction that is the difference between valid free-field measurements and System J measurements made under identical pressure and temperature conditions.

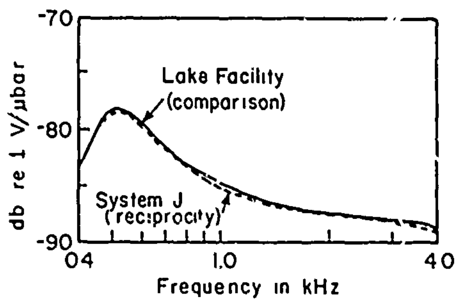

Fig. 7. Free-field voltage sensitivity, USRD type F40 transducer; open-circuit voltage.

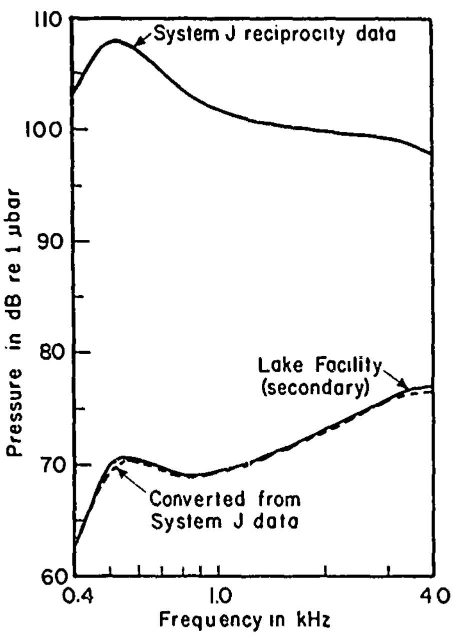

Fig. 8. Transmitting current response, USRD type F40 transducer.

A reciprocity calibration performed in the system is compared with the free-field calibration of a USRD type F40 transducer in Fig. 7. In Fig. 8, unconverted system transmitting current data of the same transducer are shown, and the converted response obtained by applying the ratio of the respective reciprocity parameters is compared with Lake Facility results. Note the constant difference in decibels between the system-measured receiving sensitivity in Fig. 7 and the transmitting response in Fig. 8, reflecting the frequency independence of the plane-wave reciprocity parameter. In Fig. 9, a reciprocity calibration on one of the system detection probes is compared with its Lake Facility secondary calibration. Figure 10 shows the effect of orientation on the free-field voltage sensitivity of an experimental short line hydrophone and shows that the results of the end-on orientation in the chamber follow those in the lake. The

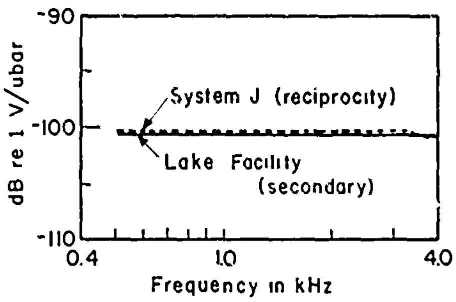

Fig. 9. Free-field voltage sensitivity, USRD type ?40 probe used in System J; open-circuit voltage.

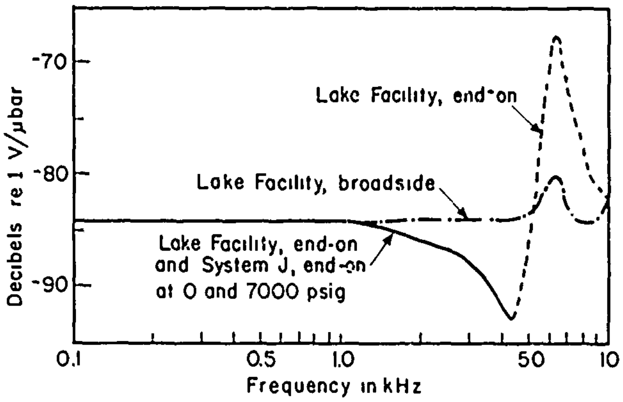

Fig. 10. Free-field voltage sensitivity (secondary calibration), experimental USRD line hydrophone, showing effect of orientation; open-circuit voltage.

effects of pressure, temperature, and orientation are further shown in Fig. 11 for another experimental hydrophone, shown in the rigging cage of Fig. 3. In general, size limitations on instruments had been estimated to be about 13 cm dia and 91 cm long, but the over-all length of this particular hydrophone was 109 cm.

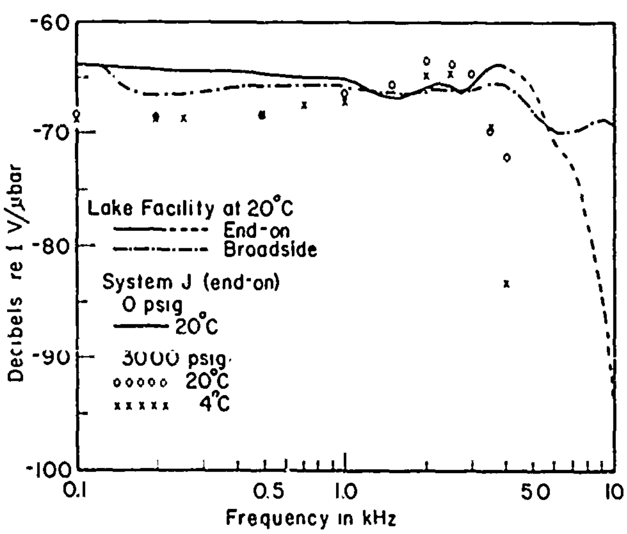

Fig. 11. Free field voltage sensitivity (secondary calibration), experimental USRD hydrophone, showing effects of pressure, temperature, and orientation; open-circuit voltage.

CONCLUSION

The design goals of the new facility have been met fully. The facility is being operated regularly, both on routine and research problems. As a result, the Navy now has a new and unique capability in the field of underwater sound calibration.

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Transducers - Test facilities						
Transducers - Calibration						
Impedance tubes						
Low frequency						
High pressure						
Pressure vessels						